

By the Light of the Sea

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January 25, 1995: On a dark evening in the Arabian Sea off the coast of Somalia, a merchant vessel was steaming southward when its crew began to notice a strange glow in the distance. Within minutes, and for six hours thereafter, the S.S. *Lima* found herself cutting through waters producing a radiant white glow reminiscent of a boundless snowfield. Ten years later, scientists learning of *Lima*'s surreal encounter sought out the date and time within an archive of low-light satellite data. The match found between the ship's position and an "anomalous" light source in the satellite data — spanning an area exceeding 15,000 km² and morphing over several night's time in a way consistent with the known sea surface currents — marked the first confirmed remote-sensing of the legendary "milky sea," a poorly understood phenomenon thought to be linked to population explosions of luminous bacteria. Here, we detail the unusual circumstances and important implications of this discovery.

INTRODUCTION

Most maritime cultures hold a rich tradition of folklore and legends of The Deep. Whether tales of ship-eating sea monsters and beautiful mermaids are purely the wild fabrications of weary-minded sailors consumed by superstition and prone to exaggeration, or whether they may sometimes harbor an inkling of truth, is the irresistible question that captures the imagination. Our role as scientists is to seek out physically plausible, natural explanations for what might appear to others as supernatural phenomena. In some cases, the truth revealed can be stranger than the fiction we originally sought to dispel.

For centuries, the "milky sea" was just another in a long list of improbable tales spun by colorful seafarers. As suggested by the name, milky seas describe vast expanses of seemingly white water. Since milky seas are strictly nocturnal phenomena, occurring particularly under very dark, moonless conditions, the light observed from them is not the reflection of a down-welling source of radiation (e.g., moonlight) but instead a true emission from something within (or perhaps floating atop) the water. Long before their scientific acknowledgment, milky seas were a well-entrenched part of maritime folklore. Eventually they found their way into classic sea-adventure fiction novels of the mid-19th century such as Jules Verne's *Twenty Thousand Leagues Under the Seas* and Herman Melville's *Moby Dick*, the authors no doubt drawing from the many ship reports available to them at the time.

For example, in 1832 the crew of the *Clive* felt they were in mortal danger when between Bombay and the Arabian Gulf their ship entered white waters that obscured the line of horizon and eliminated all visual indications of forward movement (due to the complete uniformity of the glow and associated loss of depth perception). The crew of the *Moozuffer*, transecting these same waters in 1849, described the ship "forcing her way through molten lead" while the stroke of the paddle wheel churned liquid resembling patches of "thick milk or cream." In 1854, the *Shooting Star* reported crossing an ocean surface shining bright enough to illuminate objects on deck and to produce on the horizon the appearance of an aurora borealis. En route to Bombay in 1856, the steamship *Singapore* encountered an ocean glowing with such brilliance that its captain was fooled into thinking that distant clouds (being illuminated by the sea) were in fact land features, and that they had somehow drifted far off course!

According to Herring and Watson,¹ at least 235 similar encounters have been logged by captains and crew since 1915, predominantly in the waters of the northern Indian Ocean (171 reports) and off Indonesia (40 reports). Despite being based on layman observations, the accounts are surprisingly consistent. It was not until 1985 that a research vessel operating in the western Arabian Sea happened upon a milky sea and collected samples for analysis.² Water samples from the three-day-long event suggested the cause to be a bloom of the luminous bacteria *Vibrio harveyi*, which were found to be colonizing upon the brown/green alga *Phaeocystis*, perhaps in the form of a surface slick.

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This study remains the lone scientific encounter with a milky sea, due largely to the remote, episodic, and transient nature of these events. Now, with the help of low-light satellite observing systems, we may finally have a means for detecting, tracking, and characterizing the elusive milky seas remotely.

BIOLUMINESCENCE AS THE “LACTOSE” OF MILKY SEAS

Before presenting the satellite results, it is worth expanding here on the leading hypothesis for milky seas. Bioluminescence is a special class of chemical luminescence (chemiluminescence) that takes place within a living organism. Light is produced as the by-product of a luciferase-catalyzed oxidation of reduced flavin mononucleotide and a long-chain aldehyde. Quite unlike the familiar dinoflagellate-produced bioluminescence events, characterized by local flashes of light in the immediate vicinity of disturbed waters (e.g., breaking waves along the seashore during red tide blooms, or in the turbulent wakes behind ships), the glow emanating from a milky sea is reportedly constant, opaque, widespread, and entirely independent of mechanical stimulation.

For this reason, the most likely scientific explanation for milky seas is luminous bacteria (consistent with the observations of Lapota et al.²), which are known to produce a faint but steady glow (Fig. 1) when their populations reach a critical concentration. Requirements for this process to occur are (i) an abundance of oxygen in the water, (ii) sufficiently high



FIGURE 1
Laboratory sample of the luminous bacteria strain *Vibrio fischeri* grown in a photobacterium broth. The central emission wavelength of ~500 nm gives the appearance of blue/green light.

concentrations of a chemical called *autoinducer* that is produced and detected by the organism (a cell-to-cell communication process referred to as “quorum sensing,” which tells the colony when to begin emitting light), and (iii) an extremely high concentration of bacteria (e.g., about 10^8 cells·mL⁻¹).

By standards of human vision, the light levels produced by the most intense of milky seas are considered to be rather faint. Under low-light viewing conditions (scotopic vision), the rod cells of the human eye’s retina operate as the primary photodetectors. Unlike the cone cells we use under brighter illumination, which provide three distinct visible band-passes (blue/green/red), the rods do not provide this same color discrimination capability. For this reason, even though the central wavelengths for most bioluminescent light emissions are near 500 nm (blue/green light), a milky sea would still appear white (or in the most extreme cases, perhaps having a hint of cyan as in Fig. 1). Although the absolute value of luminescence is very low, its contrast against dark, moonless skies would be perceived by the dark-adjusted eye as brilliant.

The reason bacteria would want to produce light — a costly practice from an energy standpoint — is rather interesting in its own right. In contrast to dinoflagellate organisms, which produce a bright and transient flash of light to ward off predators (ironically enough, by attracting still larger predators, higher in the food chain, to the area), prokaryotes such as luminous bacteria are thought to glow for precisely the opposite purpose—they *want* to be ingested. It so happens that the gut of a fish is a preferred habitat for these bacteria, so when they gather in a sufficient concentration (e.g., colonization upon organic matter) they take advantage of their ability to emit light in order to solicit themselves to potential hosts who are capable of sustaining that population. Under normal conditions, this might occur on an isolated piece of material, making it stand out from its surroundings. In the case of milky seas, the uniqueness factor would be lost for the sheer numbers of colonized substrata.

AN UNLIKELY PATH TO AN UNLIKELIER DISCOVERY

The series of events leading to the first detection of a milky sea from space began, strangely enough, as a lunchtime chat among colleagues attending a meteorology conference in Seattle. The discussion centered on the anticipated capabilities of the Day/Night Band (DNB), a new sensor being developed for the National Polar-orbiting Operational Environmental Satellite System (NPOESS) Visible/Infrared Imager/Radiometer Suite (VIIRS). We knew about the unique nighttime imaging capabilities of the DNB’s heritage sensor, the Defense Meteorological Satellite Program (DMSP)

Operational Linescan System (OLS), which employs a photomultiplier tube (PMT) to amplify extremely low levels of light (occurring at four to five orders of magnitude below the limits of other visible-light detectors designed for daytime observations). This high sensitivity enables detection of cloud and snow cover at night by way of reflected moonlight. It also can detect both natural (e.g., forest fires, lightning, aurora) and artificial (e.g., city lights, oil refinery gas flares, fishing fleets) sources of light. We were curious as to whether the NPOESS VIIRS/DNB, with its superior spatial and radiometric resolution, would find other kinds of weak/fine-scale light features.

To our knowledge, there were no documented cases of OLS-detected bioluminescence, presumably due to the small spatial extent and low levels of light produced by typical events. Could the DNB do better here? Stepping back, and perhaps naively so, we wondered whether certain bioluminescent events ever occurred at scales sufficient to “fill” a typical satellite pixel (i.e., of order 1 km^2 , thereby increasing their odds of detection), such that even the OLS might stand a chance of spotting them.

And so, as any noble scientists of the 21st century might do, we ran a “Google” search on the words “bioluminescence” and “widespread.” The results led us almost immediately to a report submitted by James P. Briand, then captain of the British merchant vessel S.S. *Lima*, to the journal *The Marine Observer*:

25 January 1995: At 1800 UTC on a clear moonless night while 150 n.mile east of the Somalian coast a whitish glow was observed on the horizon and, after 15 minutes of steaming, the ship was completely surrounded by a sea of milky-white colour with a fairly uniform luminescence. The bioluminescence appeared to cover the entire sea area, from horizon to horizon [...] and it appeared as though the ship was sailing over a field of snow or gliding over the clouds [...] The bow waves and the wake appeared blackish in colour and thick black patches of oil were passing by. Later, the Aldis lamp revealed that the ‘oil patches’ were actually light green kelp, amazingly black against the white water.³

In addition to supplying specific information on the date, time, and location of the event, Capt. Briand’s report went on to include the *Lima*’s course and temperature/pressure/wind data. Realizing that the National Geophysical Data Center (NGDC) began archiving OLS data (“smooth” format or approximately 2.8 km spatial resolution) in 1992, we were optimistic about the prospects of obtaining coverage over the *Lima*’s location by one or more of the contemporary DMSP constellation members.

Our Internet search tactic proved faithful once again in guiding us to several bioluminescence experts whose input would add both substance and context to our observations. Also among those contacted were experts in the field who had dismissed altogether, based on previous failed attempts, the prospect of any possible detection with current satellite technology. Realizing the many challenges we faced from an observing system standpoint, it would be nearly impossible for us to counter their arguments with anything short of clear and definitive proof to the contrary.

AGAINST ALL ODDS

As luck would have it, several candidate OLS orbits were indeed available in the NGDC archive for the days surrounding the *Lima* report, including one evening pass collected within an hour of the initial sighting. Another thing going in our favor was the relative absence of moonlight during this period, meaning that the OLS sensor would be operating very close to its highest gain setting. Even so, we knew that our chances of detecting above the noise the very low light signals of a milky sea remained slim, hinging on an opportune positioning of the feature within the sensor’s 3000 km swath.

The OLS implements a pendulum-like cross-track scanning motion to image a scene, meaning that its footprint (the projection of the detector element onto the surface of the Earth) grows with increasing angle off nadir (similar to the spot-size of a flashlight pointed at the ground). In an attempt to preserve a near constant spatial resolution across the entire swath, the OLS mechanically decreases the size of its detector (and hence, its footprint) with increasing scan angle. At about ± 766 km off nadir, the first of these discrete deflections is clearly evident when viewing the imagery in a low-end enhancement. The regions of the imagery swath just prior to the first mechanical deflection offer the largest detector footprints, greatest signal-to-noise ratios, and hence best opportunities to detect a low-light signal. Put in terms a tennis player might understand, there exists on the OLS swath a narrow “sweet spot” offering reduced noise and therefore enhanced detection capability.

In what seemed to be a case of extreme serendipity, our target area fell repeatedly within this sweet spot on four consecutive nights, beginning with the night of the *Lima* milky sea observation. What’s more, the unprecedented level of detail in Capt. Briand’s account allowed for assignment of boundaries on the event that would prove invaluable to the data analysis to follow. The best of all possible scenarios in terms of timing and placement had stacked the odds of detection squarely in our favor. Murphy’s Law as it typically applies to scientific data gathering had never failed so miserably.

A SMUDGE ON THE SCREEN

Even with such good fortune, we would still need to rely on some amount of digital enhancement to isolate any features of interest from the considerable PMT noise present on the low end of the detector's sensitivity range. The enhancement consisted of first subtracting out the mean intensity of each scan line (removing striping), then applying along-track and cross-track filters. This retained the slightly brighter/coherent structures while tending to remove random noise.

At first glance, the faint features in the January 25–27, 1995, imagery sequence (Fig. 2(A–C)) could easily have been mistaken for run-of-the-mill finger smudges found on most computer monitor displays. It became evident only after digital enhancement (Fig. 2(D–F)) that the coherent feature, approximately 50 km

wide by 300 km long (roughly the size of Connecticut), was not an artifact of random noise (or oily fingertips) but was a recurrent feature in the data that retained its general structure for at least three consecutive nights. A colleague once said that a career in science was 99% frustration and 1% sheer exhilaration. At the moment we overlaid the reported positions of the *Lima* at both entrance and exit from the glowing waters (Fig. 2(D)), showing a nearly perfect match with the boundaries of the peculiar comma-shaped feature appearing in the enhanced OLS imagery, it became perfectly clear that this 1% made everything else worthwhile.

UPON FURTHER REVIEW

Several milky sea accounts mention accompanying phenomena. Though mysterious to early shipboard

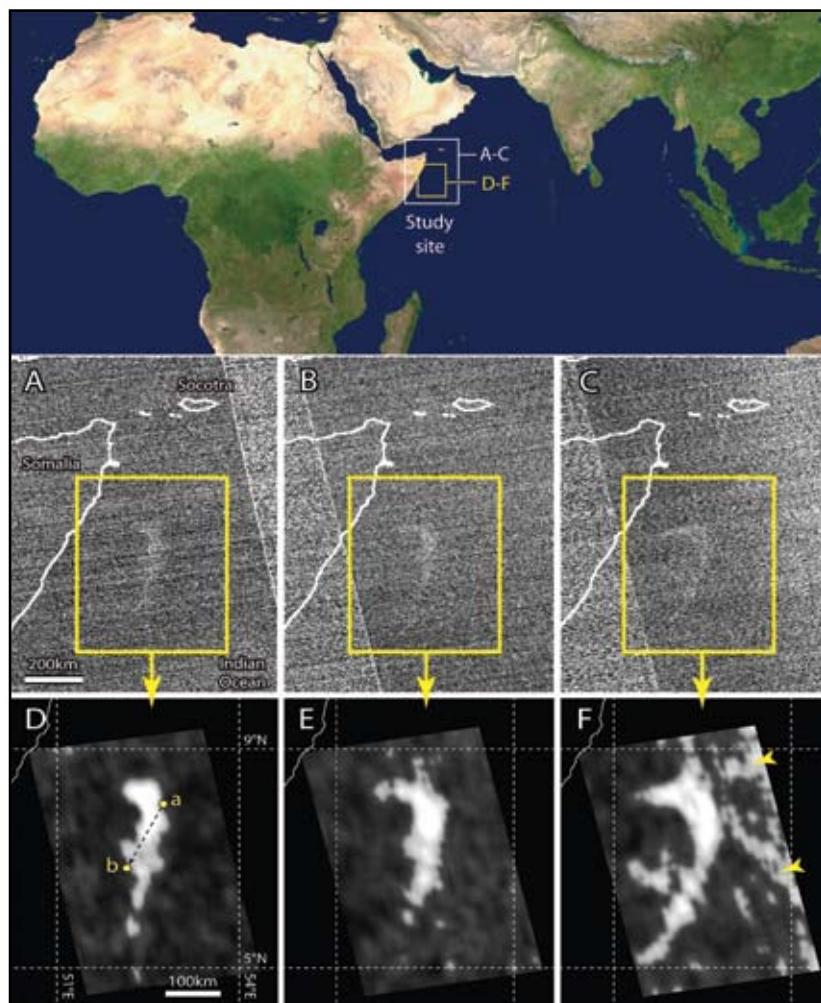


FIGURE 2

DMSP/OLS unfiltered (A–C) and digitally filtered (D–F) nighttime visible imagery for the date of the S.S. *Lima* observation (A, D: 25 Jan 1995, 1836 GMT) and the following two days (B, E: 26 Jan 1995, 1804 GMT; C, F: 27 Jan 1995, 1725 GMT), depicting a coherent bright structure just above the instrument noise. Yellow arrowheads in (F) denote noise contamination. (Figure from Ref. 4.)

observers, they now offer us clues to understanding the underlying environmental state. For example, several reports cite large sea surface temperature (SST) gradients and a sudden calming of winds when entering milky seas. Such gradients often demarcate oceanic fronts, with the cooler sides of these fronts inducing a stable boundary layer in the lower atmosphere which can decouple the surface from stronger winds aloft, resulting in a potentially rapid decrease of winds when crossing into the cooler waters. It so happens that a strong boundary exists in the region of the *Lima* milky sea encounter, formed between warmer waters transported northward by the Somali current, and the cooler, nutrient-rich waters upwelling off the Horn of Africa.

Although the *Lima* did not report any noteworthy SST or wind speed changes along its milky sea transect, we pursued nonetheless a spatial analysis of SST retrieved from Advanced Very High Resolution Radiometer (AVHRR) data and sea surface currents from the NRL Layered Ocean Model (NLOM; 1/16° resolution, courtesy of our colleagues at NRL Stennis Space Center) in order to better understand the broader environmental conditions. Figure 3(A) depicts the NLOM sea surface current field, revealing the presence of a large cool-water gyre just off the Horn of Africa. Knowledge of this eddy's existence proved key to understanding the temporal evolution of the milky sea feature (Figs. 3(B–D)), whose northern "head" appears to wrap in a counterclockwise fashion around the eddy—linking the glowing feature unequivocally to the

ocean surface. Figure 3(E) depicts the AVHRR-derived SST field (black patches correspond to clouds masked out prior to conducting the retrieval). Overlaying the *Lima*'s track upon the milky sea feature, we note that despite the presence of a strong northwest/southeast gradient in SST, the ship's course ran parallel to it. Thanks to the satellite data, we can explain the lack of an observed SST gradient for this particular case while not discounting in general the potential importance of oceanic fronts to the formation of milky seas.

Despite the fact that the OLS data were not calibrated, the known minimum detectable signal (MDS) for the sensor allowed for a conservative estimate on total light production, and by extension, the total bacteria population involved. Because the OLS sensitivity range and the bacterial light emission spectra (Fig. 4(A)) do not overlap completely, we determined an adjustment factor (i.e., how much more would need to be produced by the bacteria in order to register the same signal as an emission source having perfect overlap with the OLS response curve). Then, knowing the per-cell light emission rate for luminous bacteria (measured in the laboratory), we could compute the minimum population of cells in the near-surface water column required to produce light levels equaling this adjusted MDS. Finally, using the satellite-inferred spatial extent we computed the total bacterial population.

Following the above procedure, the MDS and adjusted MDS values were $4 \times 10^{-5} \text{ W} \cdot \text{m}^{-2} \cdot \text{sr}^{-1}$ and $1.8 \times 10^{-4} \text{ W} \cdot \text{m}^{-2} \cdot \text{sr}^{-1}$, respectively; the per-cell emis-

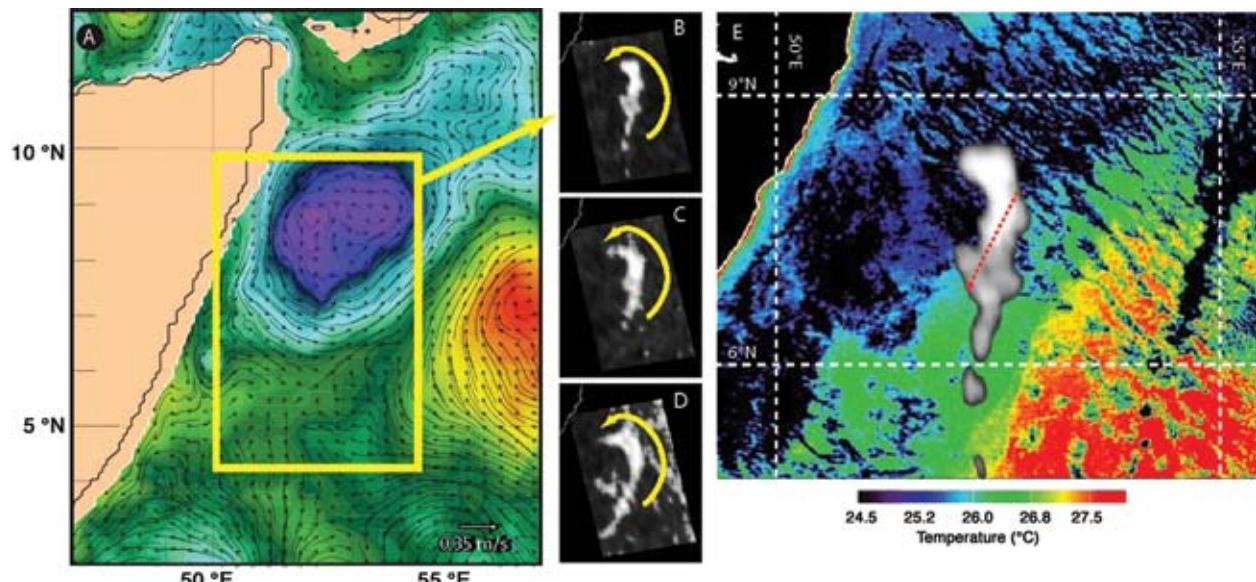
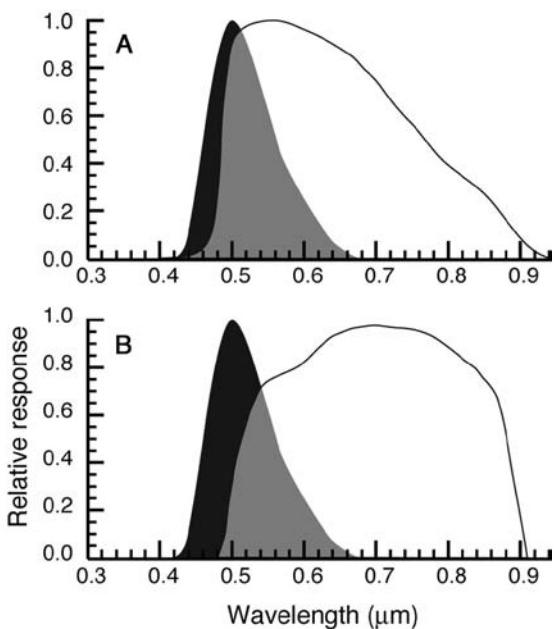


FIGURE 3

NLOM sea surface currents (A) for date of the S.S. *Lima* observation. Yellow box corresponds to the study area at right (B: 25 Jan 1995, 1836 GMT; C: 26 Jan 1995, 1804 GMT; and D: 27 Jan 1995, 1725 GMT). Blue/purple colors correspond to low values of surface height anomaly, depicting cold eddy. AVHRR-retrieved SST (E) reveals orientation of the milky sea with respect to a gradient, with S.S. *Lima* transect shown as a red dashed line. (Figure from Ref. 5.)

**FIGURE 4**

Laboratory emission spectra of bioluminescent bacteria (solid black) compared with spectral response functions for (A) the DMSP OLS nighttime visible band of the sensor used in this study, and (B) the NPOESS VIIRS day/night band. Spectral overlap areas shown in gray. (Figure from Ref. 4.)

sion was $1.2 \times 10^3 \text{ phot} \cdot \text{s}^{-1} \cdot \text{cell}^{-1}$; minimum detectable population was $1.9 \times 10^8 \text{ cells} \cdot \text{mL}^{-1}$ (within the top 10 cm of water); and the milky sea surface area (for January 25, 1995) was $15.4 \times 10^3 \text{ km}^2$. This resulted in a conservative total population estimate of 4×10^{22} bacteria. The sheer enormity of this figure, representing nearly the same number of bacteria as are estimated to occupy the upper 200 m of the all the world's open oceans (non-coastal) under normal conditions, might be put into context in the following way: if each cell were scaled to the size of a grain of sand, one could form a 10 cm thick layer covering the *entire Earth!*

THE QUEST CONTINUES

There are still far more questions than answers surrounding milky seas, foremost among them: what chain of events could lead to such a massive bacteria population explosion, and do these special circumstances tell us something important about the current/future states of the marine ecosystem or climate? Equally vague is our understanding of whether milky seas occur exclusively in association with algal blooms, or whether other sources of nutrients (e.g., deep water upwelling common in these highly productive waters) may play an important role. Laboratory work ongoing at NRL in Washington, DC, and at the University of Maryland, including the setup of *Vibrio harveyi/Phaeocystis* co-cultures, may help determine preconditioning requirements and the nature of bacterial "super blooms."

As outlined above, the ability of contemporary satellite sensors like the DMSP/OLS to observe the weak signal of milky seas requires serendipitous circumstances almost as uncommon as the events themselves. Among planned satellite observing systems, the VIIRS/DNB offers the only realistic hope for pursuing this research further. The primary challenge, depicted in Fig. 4(B), is that despite the improved fidelity of the DNB compared to the OLS, its spectral band pass provides even less overlap with the bioluminescent emission spectra for bacteria thought to be responsible for milky seas. By arguments stated earlier, the light production would need to be roughly a factor of two greater to be detected with this red-shifted band pass. Since the DNB will not offer an improved MDS over that of the OLS, we can only hope that reduced noise levels will mitigate the lower detector responsivity.

Until then, we will continue pursuing new leads on possible milky sea events. The maritime record, based on a sparse sampling and biased predominantly toward major shipping routes, gives little insight into the full spatial extent, global distribution, and temporal variability of milky seas. The phenomena apparently are not limited to the Arabian Sea — there have been sightings from cruise liners off the coast of Brazil, in the waters west of central Mexico, throughout the Arabian Gulf, and in the Mergui Archipelago of Indonesia. It is entirely possible that milky seas occur in other regions, less frequented by sea vessels, as well. We encourage those who believe they may have encountered a milky sea during their travels to contact us.

SUMMARY AND CONCLUSION

In retrospect, 2005 was something of a banner year for novelist Jules Verne. Within weeks of publication of these milky sea findings,⁴ news broke of the first confirmed photograph of a live giant squid, similar to the one that mistook Verne's *Nautilus* vessel for food in *Twenty Thousand Leagues Under the Seas*. Ironies linking the milky sea findings to this novel and to history itself are at times striking: (i) according to Buist,⁶ in the early 1830s a real ship called *Nautilus* crossed a milky sea near the same location as the *Lima*, (ii) encounters by the fictional *Nautilus* and the actual *Lima* and *Moozuffer* occurred within days of each other (January 25–27), (iii) the scale of the novel's milky sea was similar to the one observed in 1995, and (iv) the story's protagonist, Prof. Aronnax, discards the possibility of ever being able to compute the number of "infusoria" responsible for such an event — a calculation afforded for the first time by the satellite observations.

While unfortunately the lost city of Atlantis was not discovered in time to round out the emerging "*Twenty Thousand Leagues...*" newsreel, we have perhaps seen enough to have a modest epiphany: the

Earth remains a place brimming with natural mysteries. Stories such as these in many ways transcend the science, touching the lives of all peoples and cultures. Even as we look to other planets, solar systems, and the cosmos beyond as the new frontiers of science discovery, it is somehow both refreshing and humbling to be confronted with evidence that such frontiers still exist in our own back yard. By the light of the sea we have gained a new sense for how very little indeed we really know about the place we call "home."

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